



Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 01 OCT 2005		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Estimation of Bio-Aerosol Concentration from Elastic Scattering LIDAR Data				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Dugway Proving Ground				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM001851, Proceedings of the 2003 Joint Service Scientific Conference on Chemical & Biological Defense Research, 17-20 November 2003. , The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 26	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



Estimation of Bio-Aerosol Concentration from Elastic Scattering LIDAR Data

November 11, 2003

Allen Q. Howard, Jr., George W.
Lemire and Martin S. Marshall



The Nation's Chemical & Biological Defense Proving Ground





OUTLINE



- Introduction and Application
- Relevant Theory
- Forward Model
- Noise Considerations
- Inverse Model and Simulations
- Conclusion and Future Development



The Nation's Chemical & Biological Defense Proving Ground





Introduction

- The West Desert Test Center (WDTC) at DPG uses an elastic backscatter LIDAR system to augment the tracking and characterization of bio-aerosol clouds.
- In support of DPG's test mission, hardware and software development for WDTC LIDAR capability is continuing.
- This talk is a progress report on our M&S project to estimate bio-aerosol concentration from LIDAR elastic backscatter data



The Nation's Chemical & Biological Defense Proving Ground





LIDAR Equation

A convenient form of the Lidar equation predicting the received power (in Watts), from an increment of atmosphere ΔR at range R , is

$$P(\lambda, R) = P_0 \frac{A_0}{R^2} \Delta R \beta_\pi(\lambda, \mathbf{r}) e^{-2 \int_0^R \kappa_e(\lambda) dR}.$$

Here λ is wave length, A_0 is area of the receiver telescope objective lens, β_π is the backscatter coefficient and κ_e is the extinction coefficient.



The Nation's Chemical & Biological Defense Proving Ground





Backscatter Coefficient

The backscatter coefficient β_π ($\text{m}^{-1} \text{sr}^{-1}$) is

$$\beta_\pi(\lambda, \mathbf{r}) = \int_0^\infty N(a, \mathbf{r}) \sigma_b(\lambda, a) da .$$

Distribution $N(a, \mathbf{r})$ is normalized such that

$$\rho(\mathbf{r}) = \int_0^\infty N(a, \mathbf{r}) da .$$

Here $\rho(\mathbf{r})$ is number of particles per unit volume. The Mie backscattering cross-section is

$$\sigma_b(\lambda, a) = \frac{1}{k^2} \left| \frac{1}{2} \sum_{m=1}^{\infty} (2m+1)(-1)^m (a_m - b_m) \right|^2 .$$



The Nation's Chemical & Biological Defense Proving Ground





Extinction Coefficient

The extinction coefficient $\kappa_e(\lambda, \mathbf{r})$ (m^{-1}) is

$$\kappa_e(\lambda, \mathbf{r}) = \rho(\mathbf{r}) \int_0^\infty N_1(a) \sigma_e(\lambda, a) da$$

where the extinction cross section is

$$\sigma_e(\lambda, a) = \frac{2\pi}{k^2} \Re \left[\sum_{m=1}^{\infty} (2m+1) (a_m + b_m) \right].$$



The Nation's Chemical & Biological Defense Proving Ground





Inversion of LIDAR Data

To estimate aerosol concentration, transform the measured LIDAR data to obtain

$$S(R, \lambda) = \log(R^2 P(\lambda, R) / (R_0^2 P(\lambda, R_0))) .$$

This definition then yields the explicit relation

$$\frac{d}{dR} S(R, \lambda) = \frac{1}{\rho(R)} \frac{d\rho}{dR}(R) - 2 \rho(R) \langle \sigma_e(\lambda) \rangle .$$

This equation is solved for the particle density function $\rho(\mathbf{r})$. Necessary information includes the averaged extinction coefficient $\langle \sigma_e(\lambda) \rangle$, LIDAR data $S(R, \lambda)$ and a boundary point ρ_f .



The Nation's Chemical & Biological Defense Proving Ground





Formal Analytic Solution to Aerosol Density

$$\rho(R) = [(1/\rho_f + 2 \langle \sigma_e(\lambda) \rangle \int_R^{R_f} \frac{dR'}{\tau(R', \lambda)}) \tau(R, \lambda)]^{-1},$$

where

$$\tau(R, \lambda) = e^{-[S(R, \lambda) - S(R_f, \lambda)]}$$

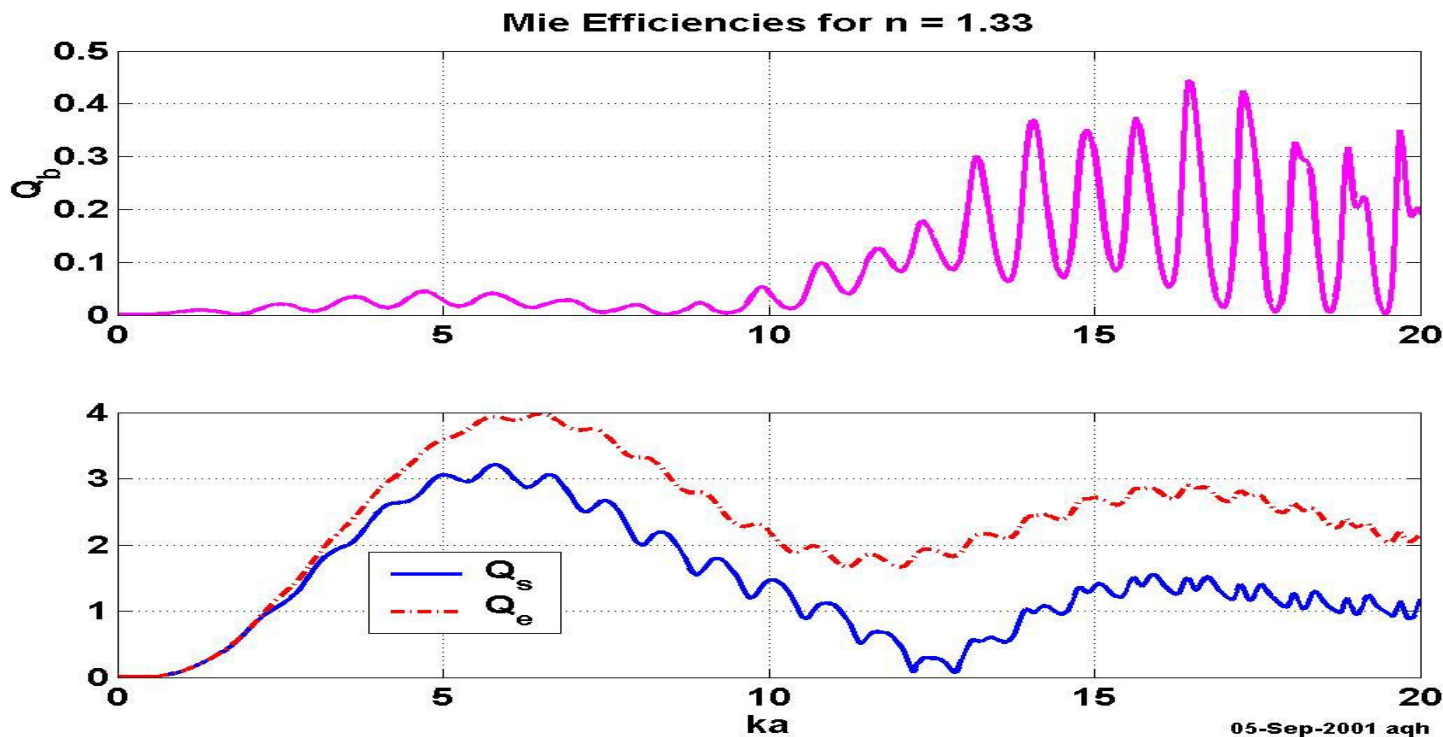


The Nation's Chemical & Biological Defense Proving Ground





Aerosol Scattering



Lidar signals are proportional to Q_b and exponentially attenuated proportional to Q_e

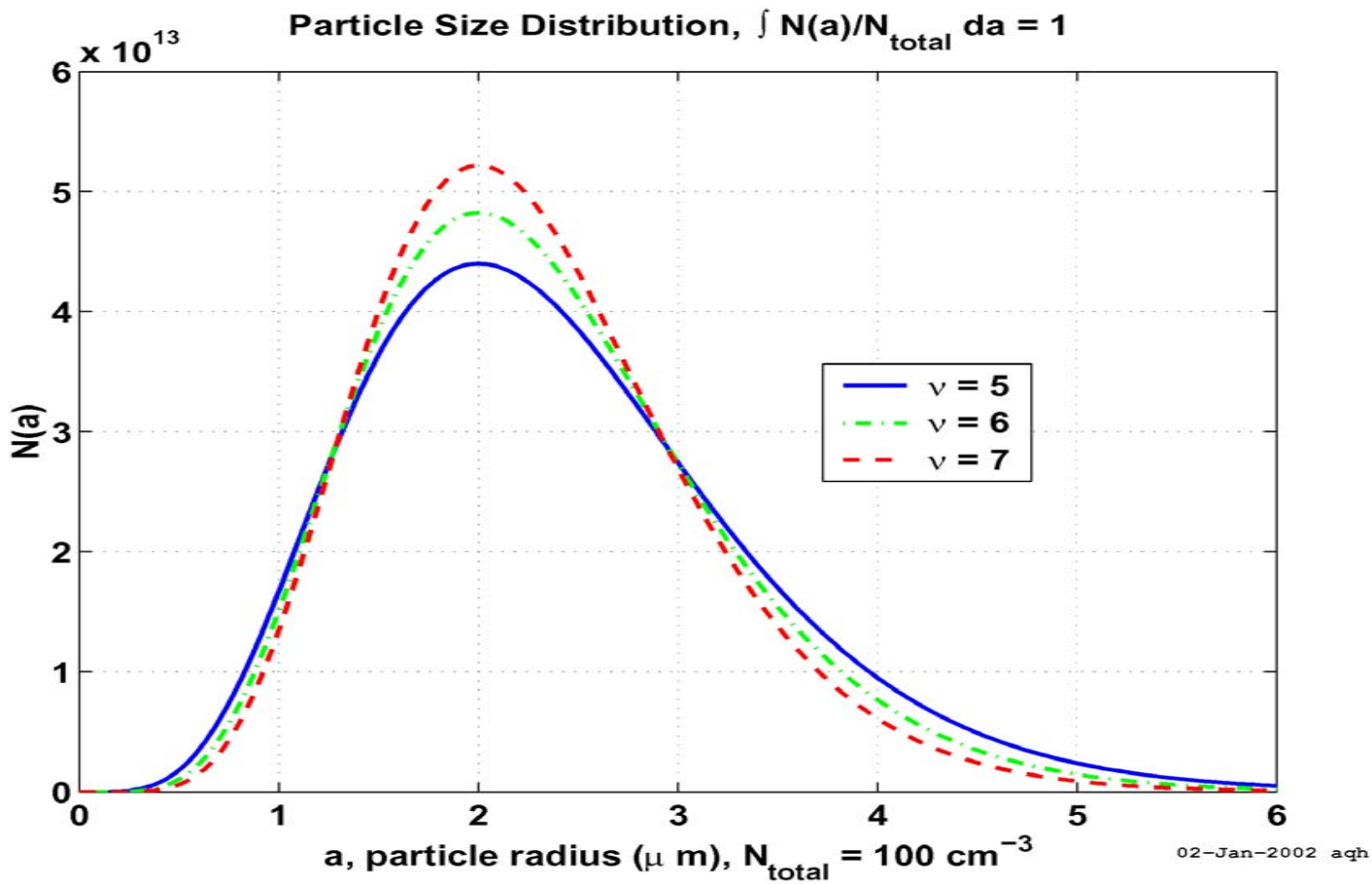


The Nation's Chemical & Biological Defense Proving Ground





Aerosol Particle Size Distribution

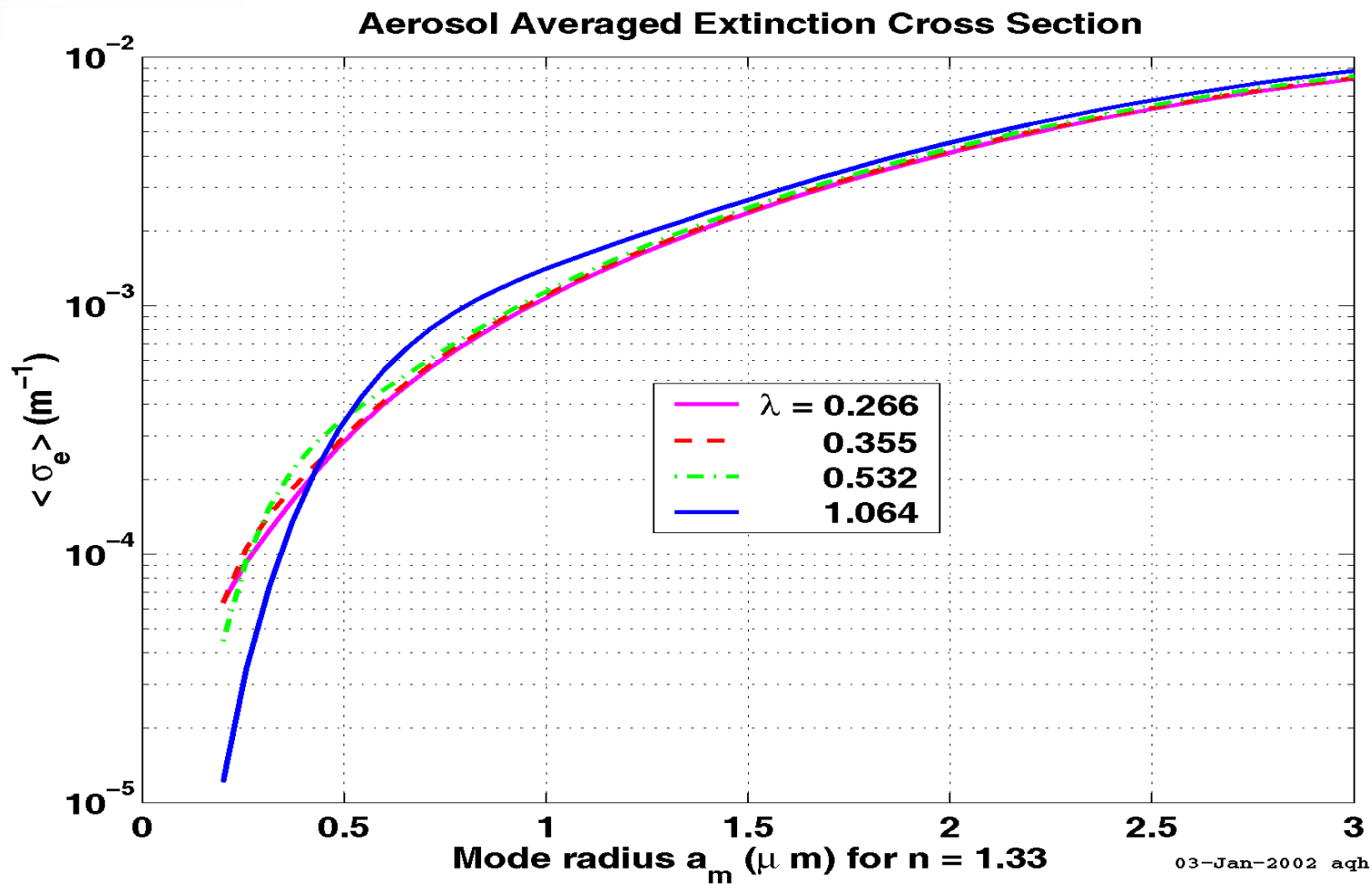


The Nation's Chemical & Biological Defense Proving Ground





Extinction Cross Section versus Aerosol Mode Radius a_m



The Nation's Chemical & Biological Defense Proving Ground

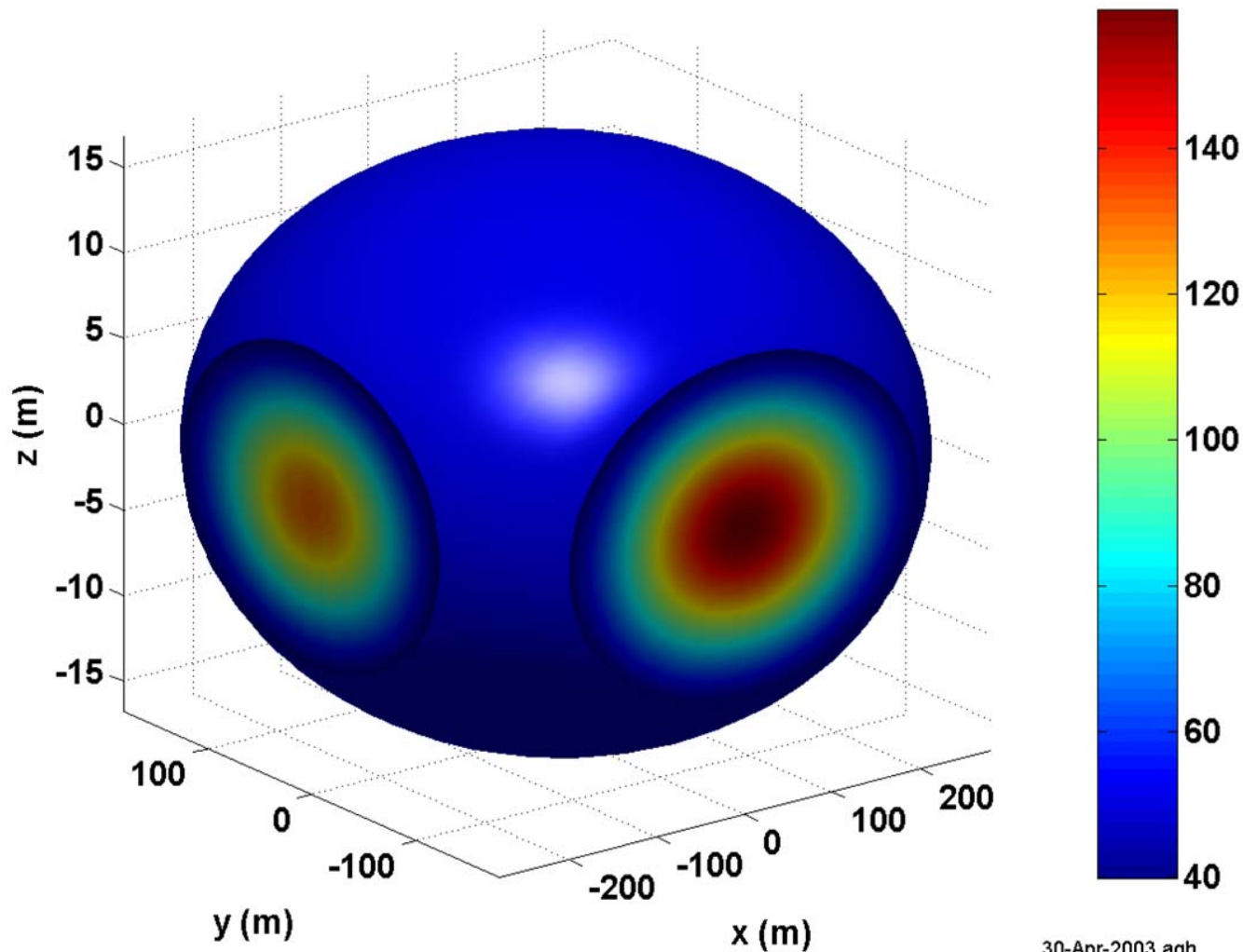




Particle Density Function



Gaussian Cloud Density $\rho(r)$ PPL

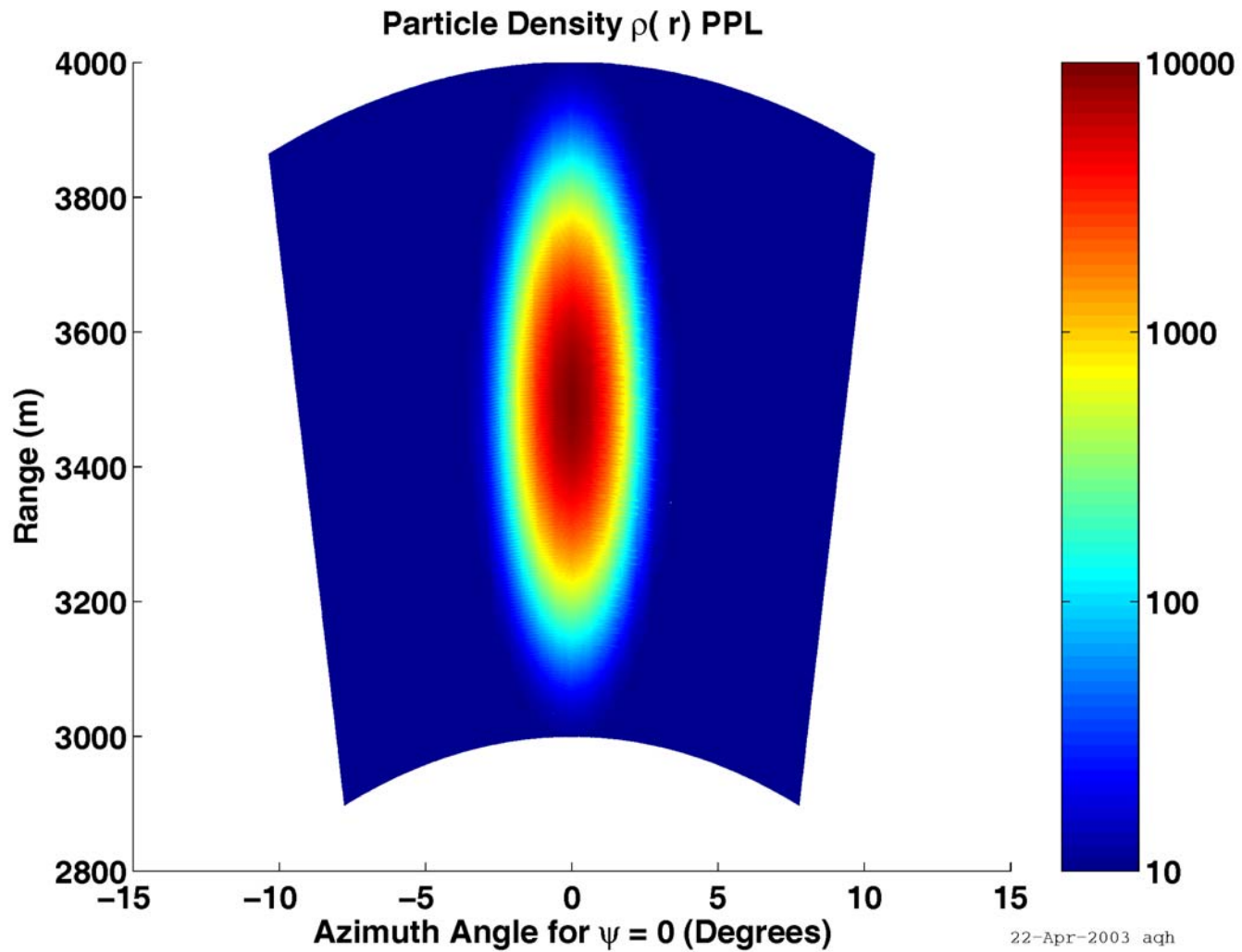


30-Apr-2003 aqh



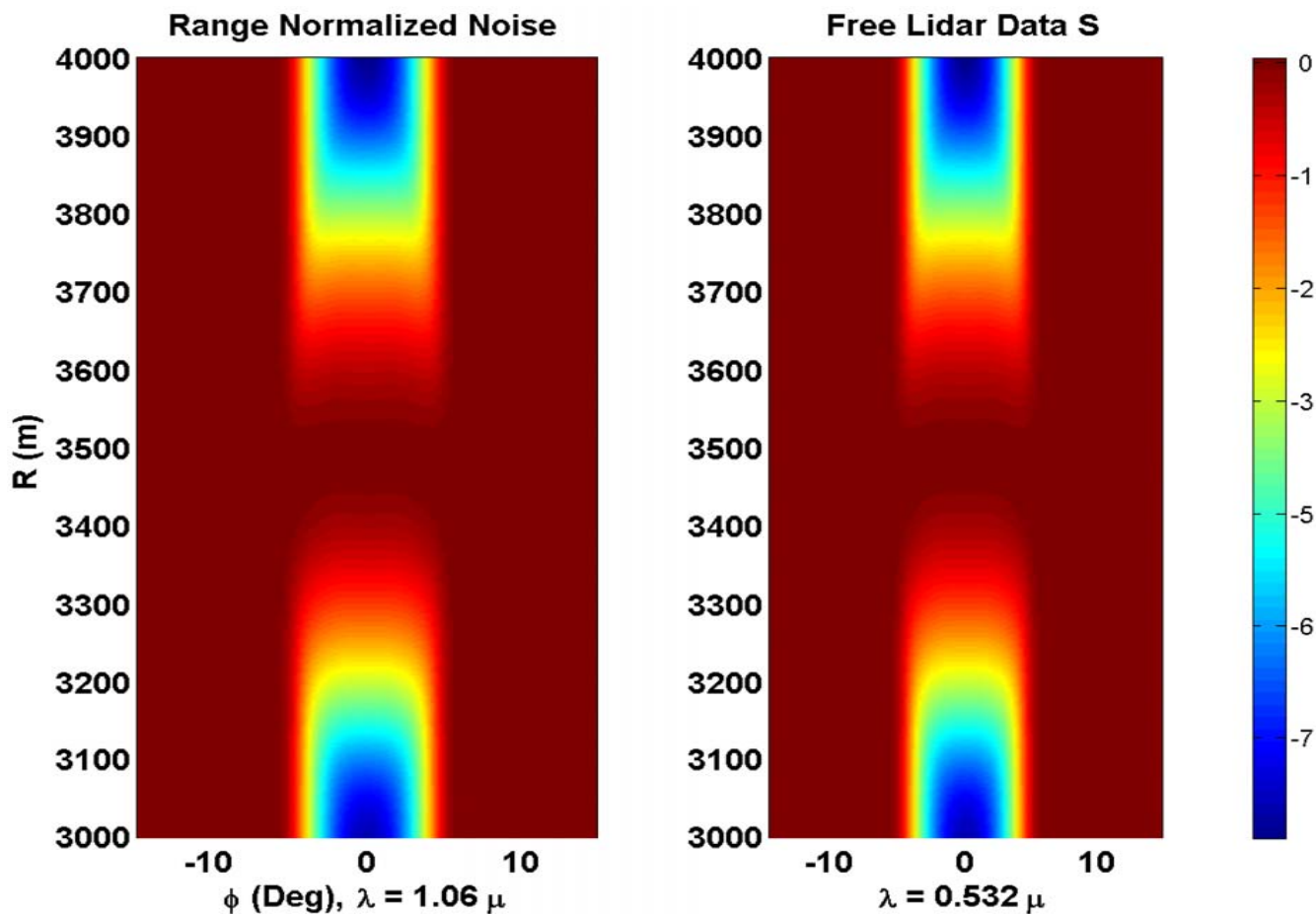


Synthetic Density Data



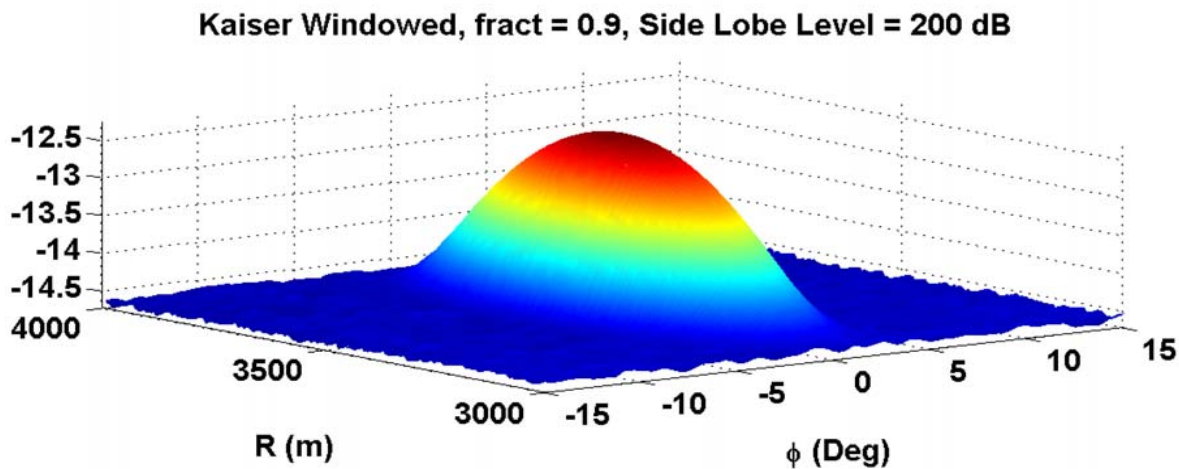
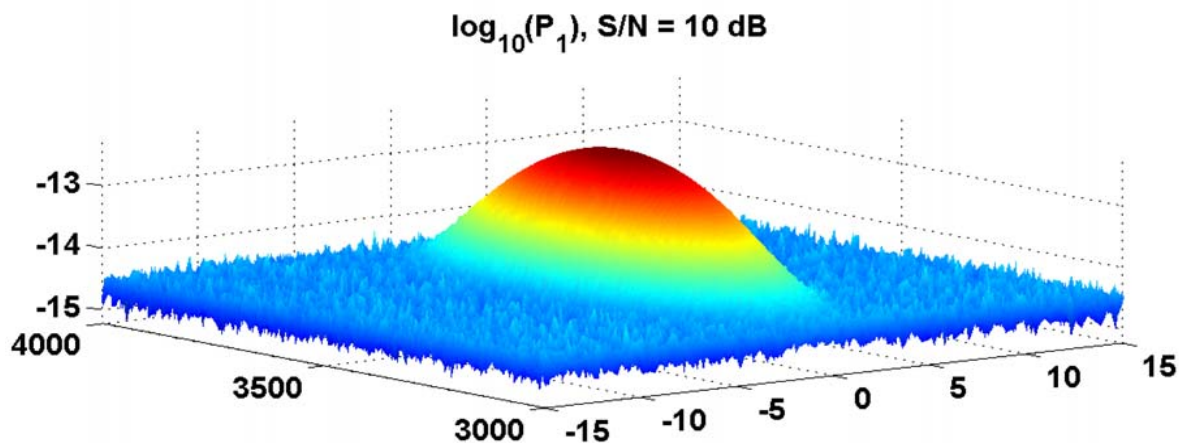


Synthetic LIDAR Data



The Nation's Chemical & Biological Defense Proving Ground
Two Frequency LIDAR data $S(R, \lambda)$ for $R_f = \frac{1}{2} R_{\max}$



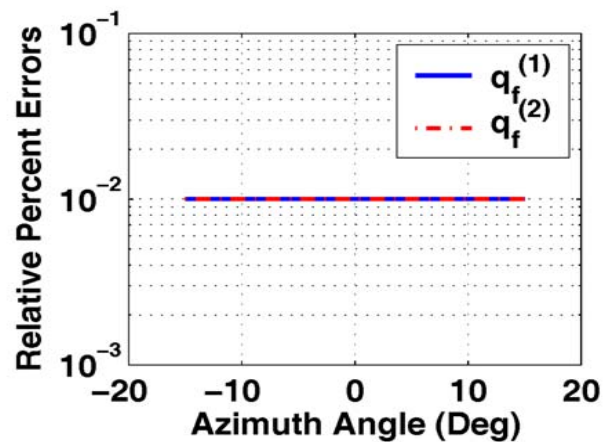
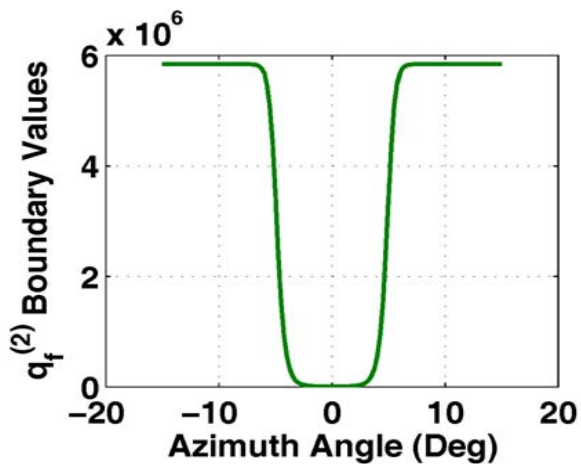
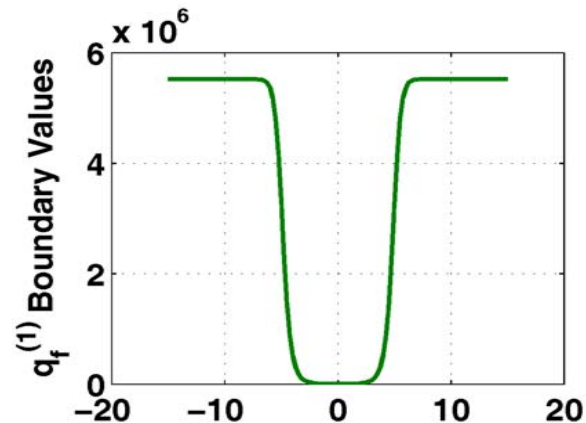
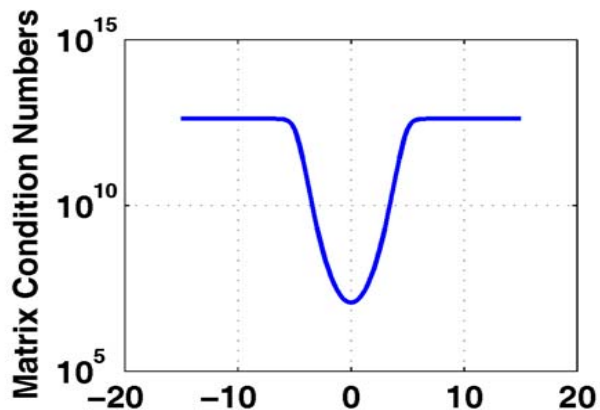


Noisy Synthetic LIDAR data $P(R, \lambda)$ for wavelength 1.064μ . Lower panel shows effect of Kaiser window with side lobe level of 200 dB.





First Stage Inversion



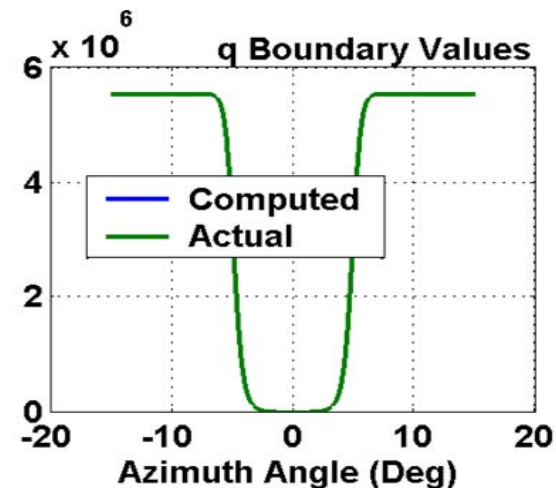
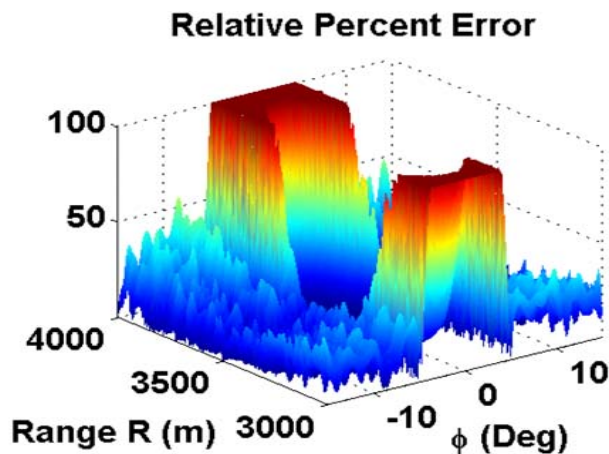
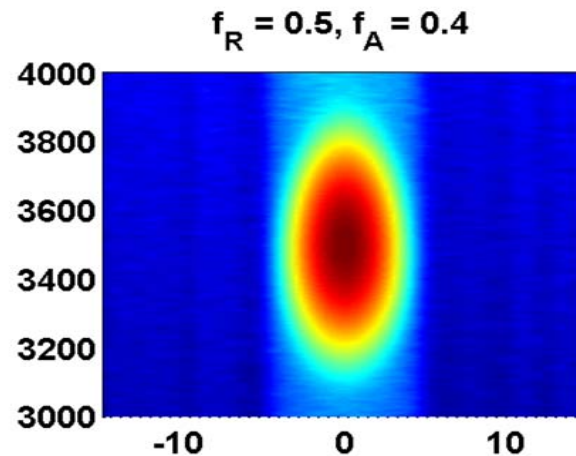
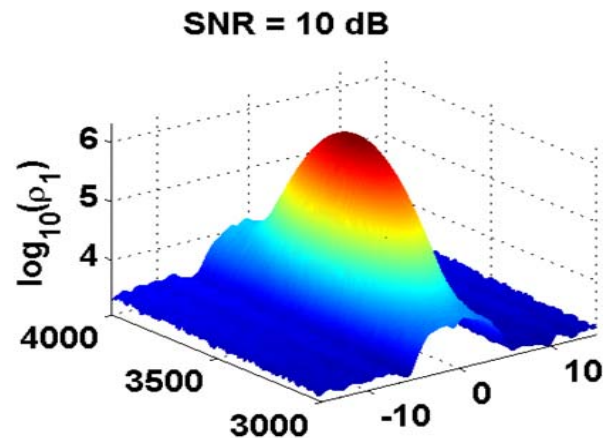
30-Apr-2003 aqh

First stage inversion results using two-frequency method.





Second Stage Inversion



30-Apr-2003 aqh

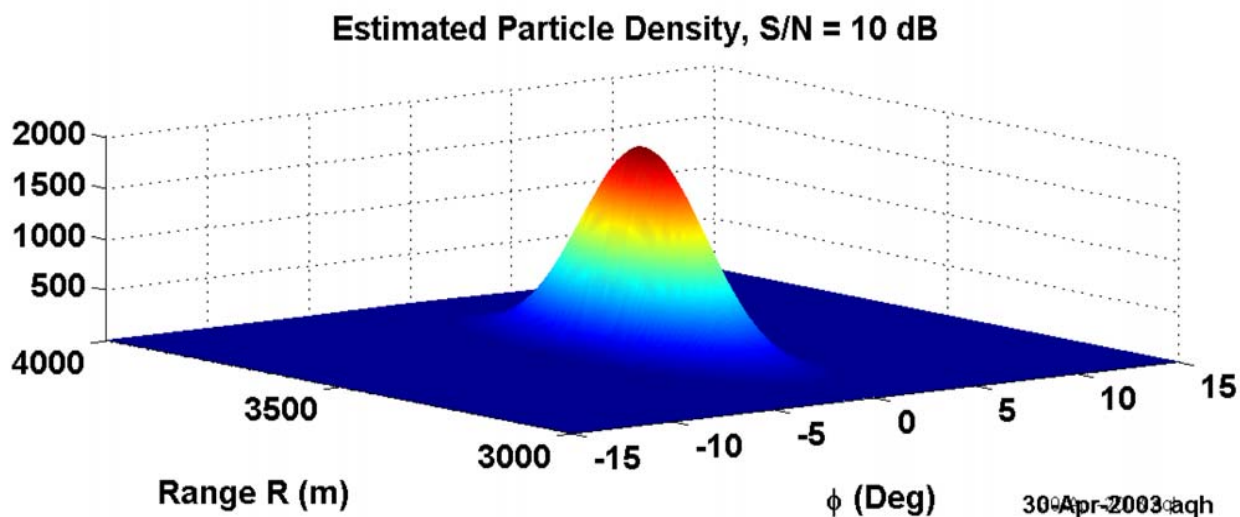
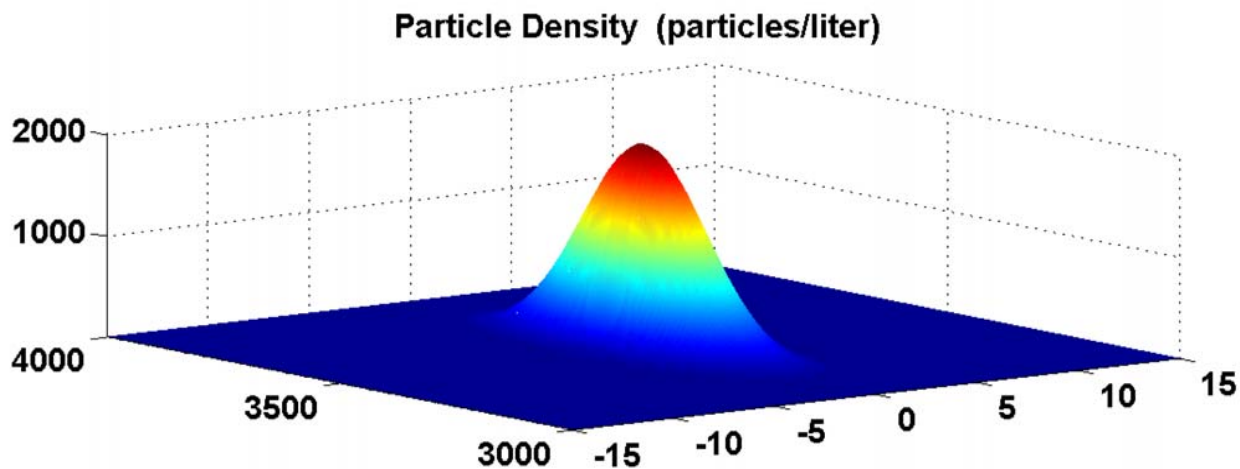


Second Stage inversion with $S/N = 10$ dB noise using equations for q_{nm} and point detector calibration.





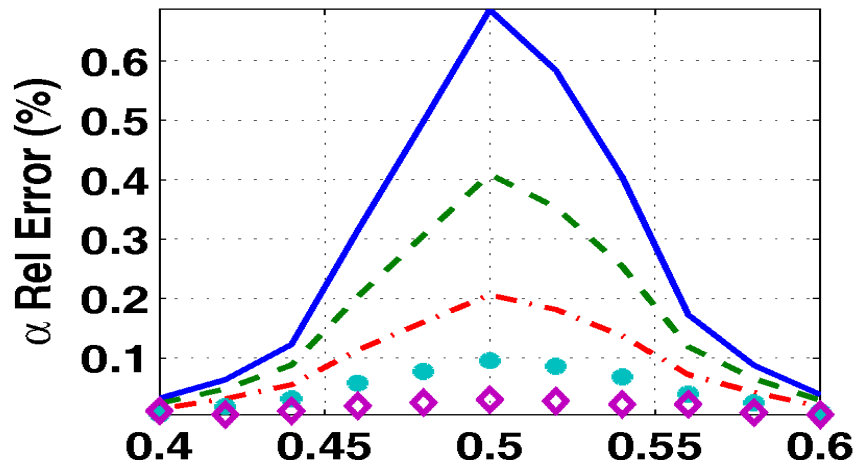
Linear Scale Inversion Results



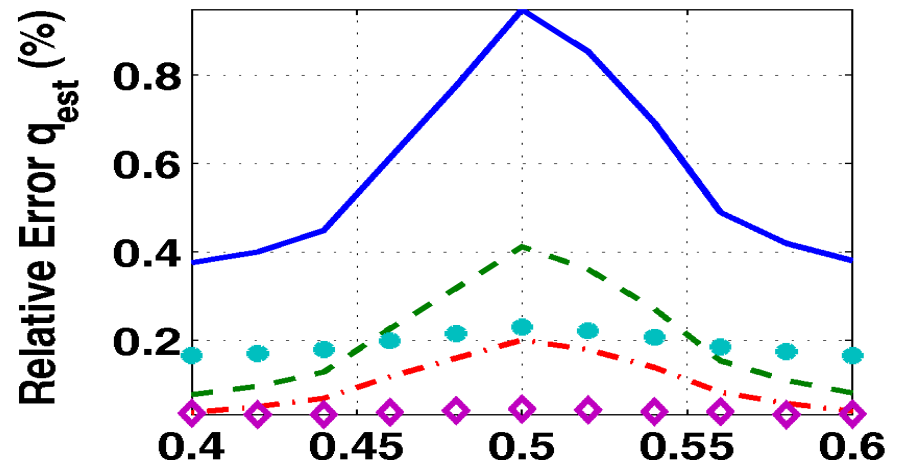
Linear scale particle density inversion in $S/N = 10$ dB noise. Upper sub-plot is exact density.



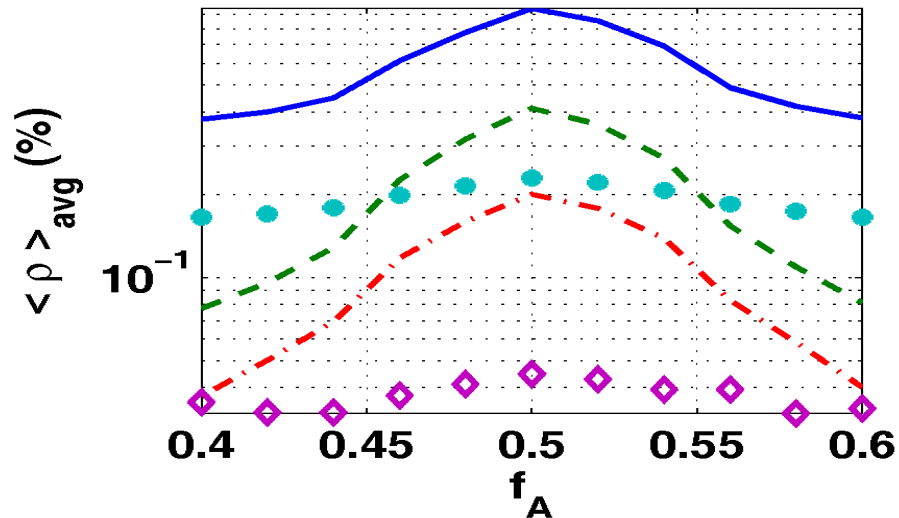
Two Frequency Method



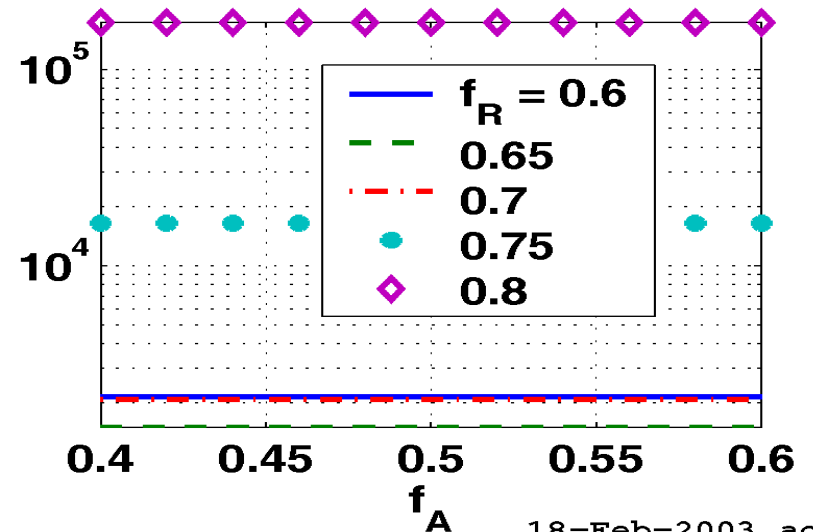
Reference Arc Estimates



Global Average



Matrix Condition Number



18-Feb-2003 aqh

Figure 11: Inversion error analysis as a function of azimuth angle fraction f_ϕ with five values of f_R as shown in the legend. Upper left-hand panel is the relative percent error in the extinction coefficient estimate $\alpha^{(1)} = 2 \langle \sigma_e(\lambda_1) \rangle$. The upper right panel displays the analogous percent relative errors in averaged boundary values q_f . Note the condition number is independent of f_ϕ .



Discrete Forward Model

$$q_{nm}^{(i)} = [V_{nm}^i + q_{fm}^{(i)}] \tau_{nm}^i,$$

where

$$\tau_{nm}^i = \tau(R_n, \phi_m, \lambda_i),$$

$$\tau(R, \phi, \lambda_i) = \exp[S(R, \phi, \lambda_i) - S(R_f, \phi, \lambda_i)],$$

$$q_{nm}^{(i)} = q(R_n, \phi_m, \lambda_i),$$

$$q_{fm}^{(i)} = q^{(i)}(R_f, \phi_m),$$

$$q(R, \phi, \lambda_i) = 1/(2 < \sigma_e(\lambda) > \rho(R, \phi)),$$

$$V_{nm}^i = \int_{R_n}^{R_f} dR' / \tau(R', \phi_m, \lambda_i).$$





Density Calibration

$$\hat{\rho}_{nm} = \rho_{cal} q_{cal}^i / q_{nm}^i .$$



The Nation's Chemical & Biological Defense Proving Ground





Single-Ray, Two-Frequency Algorithm

$$\begin{pmatrix} T_{m,a}^{(2,1)} & v_{m,a}^{(2)} \\ T_{m,b}^{(2,1)} & v_{m,b}^{(2)} \end{pmatrix} \begin{pmatrix} q_{fm}^{(1)} \\ C^{(1,2)} \end{pmatrix} = \begin{pmatrix} v_{m,a}^{(1)} \\ v_{m,b}^{(1)} \end{pmatrix},$$

where

$$T_{m,a}^{(i,j)} = 1/N_a \sum_{n=1}^{N_a} [\tau_{nm}^i - \tau_{nm}^j],$$

$$T_{m,b}^{(i,j)} = 1/N_b \sum_{n=N_a+1}^{N_R} [\tau_{nm}^i - \tau_{nm}^j].$$



The Nation's Chemical & Biological Defense Proving Ground





where

$$v_{m,a}^{(i)} = 1/N_a \sum_{n=1}^{N_a} V_{nm}^i \tau_{nm}^i ,$$

$$v_{m,b}^{(i)} = 1/N_b \sum_{n=N_a+1}^{N_R} V_{nm}^i \tau_{nm}^i ,$$

$$N_a + N_b = N_R.$$



The Nation's Chemical & Biological Defense Proving Ground





Single-Ray, Three-Frequency Algorithm



$$\begin{pmatrix} T_{m,a}^{(2,1)} & 0 & v_{m,a}^{(2)} & 0 & 0 \\ T_{m,b}^{(2,1)} & 0 & v_{m,b}^{(2)} & 0 & 0 \\ T_{m,a}^{(3,1)} & 0 & 0 & v_{m,a}^{(3)} & 0 \\ T_{m,b}^{(3,1)} & 0 & 0 & v_{m,b}^{(3)} & 0 \\ 0 & T_{m,a}^{(2,3)} & 0 & 0 & v_{m,a}^{(2)} \\ 0 & T_{m,b}^{(2,3)} & 0 & 0 & v_{m,b}^{(2)} \end{pmatrix} \begin{pmatrix} q_{fm}^{(1)} \\ q_{fm}^{(3)} \\ C^{(1,2)} \\ C^{(1,3)} \\ C^{(3,2)} \end{pmatrix} = \begin{pmatrix} v_{m,a}^{(1)} \\ v_{m,b}^{(1)} \\ v_{m,a}^{(1)} \\ v_{m,b}^{(1)} \\ v_{m,a}^{(3)} \\ v_{m,b}^{(3)} \end{pmatrix} .$$



The Nation's Chemical & Biological Defense Proving Ground





Conclusion & Future Work



- 2 and 3 frequency elastic scattering algorithms for particle density have been developed.
- At least 2 frequencies are necessary to determine reference arc values ρ_f .
- Ongoing work includes background removal, first stage signal-to-noise enhancement, and system conditioning.



The Nation's Chemical & Biological Defense Proving Ground

